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Critical Fluctuations in Beam-Plasma Systems and Solar Type III Radio Bursts

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Abstract. It is shown that the Langmuir waves are excited similar to critical fluctuations during phase transitions when the negative absorption due to electron beam traveling radially outward in the solar atmosphere is balanced by the positive absorption due to collisions in the corona and due to scattering on electron density inhomogeneities in the interplanetary medium. The effective temperature of the Langmuir fluctuations range from 10^{11} to 10^{13} K, explaining the majority of the type III bursts. The Rayleigh scattering and direct coupling due to density gradient as well as due to density inhomogeneities are discussed in the context of fundamental radiation and the combination scattering for second harmonic. The number density of electrons in type III beams is estimated and compared with observations. It is also shown that the stabilization of type III beams is achieved automatically since the instability does not develop in the case of critical fluctuations.

1. Introduction

For four decades the solar type III radio burst phenomenon has attracted the attention of both solar radio astronomers and space plasma physicists because of the intriguing complexity revealed by observations and theory. The direct detection of electron beams [17, 18] and Langmuir waves [10, 11] in association with type III bursts together with tracking of the type III burst sources in the interplanetary medium [4, 5] confirmed that electrons and Langmuir waves are associated with type III bursts [7, 8]. However the dynamics of type III electron beams and their interaction with the ambient plasma through the excited Langmuir waves is an unsolved problem. In order that the electron beams don't loose their energy by resonantly interacting with Langmuir waves, various nonlinear processes such as the induced scattering of Langmuir waves off the background ions in weak turbulence regime [14] and oscillating two-stream instability in strong turbulence regime [22] were invoked. However the observed electron density inhomogeneities [2, 3] do not allow Langmuir waves to grow to very high intensities as pointed out by several authors [20]. As far as the conversion of Langmuir wave energy into electromagnetic energy is concerned, there is no consensus either for the fundamental

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or for the second harmonic emission.

In the present paper we investigate the phenomenon of critical fluctuations near the boundary of the instability which is analogous to the anomalously growing fluctuations near the phase transition points called critical points [12, 23]. We show that the problems concerning the beam stabilization [25] and the estimation of the number density of beam electrons are automatically solved if type III bursts are assumed as manifestations of critical fluctuations. We also examine different physical processes involved in conversion of Langmuir into electromagnetic waves at the fundamental and second harmonic plasma frequencies.

2. Critical Fluctuations in the Beam-Plasma Systems

The effective temperature T_{eff} of Langmuir waves excited by an electron beam propagating radially outward in the solar atmosphere is determined in the linear approximation by the transfer equation:

$$\frac{dT_{eff}}{dl} = \alpha - \mu T_{eff}, \tag{1}$$

where α and μ are the emission and absorption coefficients respectively in a layer of thickness dl. The emission coefficient α is connected to the emissivity α_ω as:

$$\alpha = \frac{(2\pi)^3 \alpha_\omega}{\kappa k^2}, \tag{2}$$

where κ is the Boltzmann constant and k is the wave number. The emissivity α_ω is given by [1]:

$$\alpha_\omega = \frac{\omega_{pe}^2 \omega v_{ph}^2 m_e N_b}{6(2\pi)^{5/2} \Delta v_b v_{Te}^2 N_e} \exp(-\frac{(v_{ph} - v_b cos\theta)^2}{2\Delta v_b^2}, \tag{3}$$

where m_e is the electron mass; ω_{pe}, N_e and v_{Te} are the plasma frequency, density and thermal velocity of electrons in the ambient plasma; N_b, v_b and Δv_b are the density, velocity and velocity spread of the electron beam; ω and v_{ph} are the frequency and the phase velocity of the excited Langmuir waves. The absorption coefficient μ is determined by the absorption due to collisions (μ_c), effective absorption due to scattering on electron density inhomogeneities (μ_{sca}), Landau damping by the ambient electrons (μ_L) and negative absorption due to electron beam (μ_b):

$$\mu = \mu_c + \mu_{sca} + \mu_L + \mu_b. \tag{4}$$

The absorption due to collisions is given by:

$$\mu_c = \frac{2 v_{ph} \nu_c}{3 v_{Te}^2}, \tag{5}$$

where ν_c is the effective electron-ion collision frequency determined by the temperature (T_e) and density (N_e) as:

$$\nu_c = \frac{5.5 N_e}{T_e^{3/2}} \ln(220 \frac{T_e}{N_e^{1/3}}). \tag{6}$$

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The effective absorption coefficient due to scattering by density inhomogeneities (μ_{sca}) is given by:

$$\mu_{sca} = \frac{2v_{ph}}{3v_{Te}^2}\nu_{sca}, \tag{7}$$

where the effective damping ν_{sca} is given by the diffusion coefficient D_θ :

$$\nu_{sca} = D_\theta(\Delta\theta)^2, \tag{8}$$

where $(\Delta\theta)$ is the mean angle of deflection given approximately as:

$$(\Delta\theta)^2 \simeq (\frac{\Delta v_b}{v_b})^2 \tag{9}$$

and D_θ is given by [21, 20]:

$$D_\theta = \frac{\pi}{12}\frac{\omega_{pe}}{(k\lambda_D)^2}\frac{\bar{q}}{k}\langle\frac{\delta n^2}{n^2}\rangle. \tag{10}$$

Here λ_D is the Debye length $\bar{q}$ is the typical wave number associated with the fluctuations and $\langle\frac{\delta n^2}{n^2}\rangle$ is the relative level of density fluctuations. The absorption due to Landau damping by the ambient electrons is:

$$\mu_L = \sqrt{\frac{\pi}{18}}\frac{\omega_{pe}^2\omega^3}{k^4 v_{Te}^5}\exp(-\frac{\omega^2}{2v_{Te}^2k^2}). \tag{11}$$

In the corona, the absorption due to Landau damping can also be important due to smoothly varying nature of the density distribution as shown by [28, 27, 29]. However in the interplanetary medium it is negligibly small. In the present study we neglect it both in the corona as well as in the interplanetary medium. And also the relative level of density fluctuations increases with the radial distance in the solar atmosphere and hence we consider that in the corona the main contribution to the absorption is due to collisional damping whereas the absorption due to scattering of Langmuir waves by the electron density inhomogeneities plays the dominant role in the interplanetary medium. The absorption due to beam (μ_b) is given by:

$$\mu_b = \sqrt{\frac{\pi}{18}}\frac{\omega_{pe}^2 v_{ph}^3}{\omega v_{Te}^2\Delta v_b^2}\frac{N_b}{N_e}(v_{ph} - v_b cos\theta)\exp(-\frac{(v_{ph} - v_b cos\theta)^2}{2\Delta v_b^2}). \tag{12}$$

The value μ_b is positive for $v_{ph} > v_b\cos\theta$, whereas it is negative in the region where $v_{ph} < v_b\cos\theta$. Therefore for $(v_{ph} - v_b\cos\theta) = -\Delta v_b$,and for marginally stable condition, where the absorption μ tends to zero, we can obtain the ratio $\frac{N_b}{N_e}$ in the corona by equating μ_b to μ_c and in the interplanetary medium by equating μ_{sca} with μ_b, which can be written as:

$$\frac{N_b}{N_e} = \sqrt{\frac{13.2}{\pi}}\frac{\omega\Delta v_b^2}{\omega_{pe}^2 v_{ph}^2}\nu, \tag{13}$$

where $\nu = \nu_c$ in the corona and $\nu = \nu_{sca}$ in the interplanetary medium. The solution of equation (1) in the marginally stable condition i.e., when the negative absorption due to electron beam is approximately balanced by the damping due either to collisions in the corona or to scattering on electron density fluctuations in the interplanetary medium., i.e., optically thin case $\mu L \leq 1$ can be written as:

$$T_{eff} = \alpha L. \tag{14}$$

Here L is the thickness of the layer in which the Langmuir waves exist which is determined by:

$$L = \frac{N_e}{2|\nabla N_e|}\frac{v_{Ti}}{v_{ph}}, \tag{15}$$

where v_{Ti} is the ion thermal velocity. In the corona approximately for 100 MHz plasma frequency layer the thickness L can be approximated as $L \simeq 10^9$ cm whereas in the interplanetary medium for plasma frequency layer of 13 kHz it can be approximated as $L \simeq 4.5 \times 10^{10}$ cm.

From equation (13) for $\Delta v_b \simeq v_b \simeq 10^{10}$ cm, $\omega \simeq \omega_{pe}$ and $\nu = \nu_c$, we obtain $\frac{N_b}{N_e} \simeq 2.63\frac{\nu_c}{\omega_{pe}}$. In the interplanetary medium, since it is difficult to measure the effective damping due to scattering on density fluctuations, we evaluate it by assuming that the values for the beam density measured by [18] simultaneously with type III bursts as the critical density. Therefore for the values reported by [18], where $\frac{N_b}{N_e} \simeq 3.5 \times 10^{-5}$, $v_b \simeq 3.5 \times 10^9$ cms^{-1} and $\frac{\Delta v_b}{v_b} \simeq 0.15$, the effective damping rate (ν_{sca}) is calculated as $\nu_{sca} \simeq 0.6 \times 10^{-3}\omega_{pe}$, i.e., for $f_{pe} \simeq 13$ kHz, we obtain $\nu_{sca} \simeq 48.4$ s^{-1}. Therefore we obtain the ratio of critical beam density to electron density of ambient plasma $(\frac{N_b}{N_e})_{cri} = 5.23 \times 10^{-8}$ for $f_{pe} \simeq 100$ MHz and $\nu_c \simeq 12.5$ s^{-1}. The effective temperature of Langmuir waves emitted spontaneously by such beams as critical fluctuations can be obtained by using equations (2), (3) and (14). We obtain $T_{eff} \simeq 10^{12}$ K for $(v_{ph} - v_b cos\theta \simeq -\Delta v_b$, $v_{ph} \simeq v_b \simeq \Delta v_b \simeq c/3$, $v_{Te} = 3.89 \times 10^8$ cms^{-1} $f \simeq f_{pe} \simeq 100$ MHz and $L \simeq 10^9$ cm. In the case of interplanetary type III bursts, for $\frac{N_b}{N_e} \simeq 3.5 \times 10^{-5}$; $v_{ph} - v_b \cos\theta \simeq -\Delta v_b$; $v_{ph} \simeq 3.5 \times 10^9$ cms^{-1}; $\frac{\Delta v_b}{v_b} \simeq 0.15$; $v_{Te} \simeq 1.74 \times 10^8$ cms^{-1}; $f \simeq f_{pe} \simeq 13$ kHz and $L \simeq 4.5 \times 10^{10}$ cm, we obtain $T_{eff} \simeq 2.1 \times 10^{12}$ K.

[13] estimated the maximum value of the energy density of Langmuir waves due to critical fluctuations when the damping approaches zero as $\sqrt{g}$ by including the damping due to nonlinear interactions, where g is the plasma parameter defined as $g = \frac{1}{N_e\lambda_D^3}$. Thus approximated effective temperature is much higher than the effective temperature obtained by assuming that critical fluctuations are manifestations of spontaneous emission.

3. Conversion of Langmuir Fluctuations into Electromagnetic Waves

Various nonlinear mechanisms were proposed for conversion of Langmuir waves into electromagnetic waves at the fundamental plasma frequency f_{pe}. These are (1) spontaneous and induced scattering of Langmuir waves by thermal ions [7, 24, 19, 30, 31], (2) scattering of Langmuir waves by low frequency waves, such as ion-acoustic and whistler waves [26, 19] (3) strong turbulence processes [9, 16] and (4) gradient coupling of Langmuir waves with electromagnetic waves [6, 34, 35, 15]. In the present case, the energy density of critical Langmuir fluctuations is much less than the threshold energy densities required for the induced scattering on thermal ions, decay of Langmuir waves into electromagnetic and low frequency waves and strong turbulence. Therefore only spontaneous scattering of Langmuir waves on thermal ions and direct coupling of Langmuir waves with electromagnetic waves may be important for conversion process at fundamental plasma frequency.

The brightness temperature of electromagnetic radiation T_B emitted by Langmuir waves of effective temperature T_{eff} is given by [32]:

$$T_B \simeq \frac{c^2\Omega_L}{3v_{Te}^2\Omega_T} T_L Q \exp{(-\tau)}, \tag{16}$$

where Ω_L and Ω_T are the solid angles of Langmuir and electromagnetic waves respectively, τ is the optical depth from the source to the observer and Q is the efficiency of conversion from Langmuir to electromagnetic waves. The efficiency of conversion due to Rayleigh scattering is [7]: $Q = \frac{\omega_{pe}^4 L}{12\pi N_e c^3 v_{T_e}}$ giving 3.2×10^{-6} and 5.7×10^{-12} respectively at 100 MHz and 13 kHz. The efficiency of conversion due to gradient coupling between Langmuir and electromagnetic waves is defined by [32]: $Q = \frac{\pi v_{ph}^2}{4\Omega_L c^2}(\frac{3c}{2\omega L_n})^{\frac{2}{3}}$, where L_n is the scale length of the density variation which is $\simeq 1.7\times10^{10}$ cm and 1.5×10^{13} cm respectively making Q as 5.7×10^{-7} and 6.24×10^{-7} at 100 MHz and 13 kHz respectively. Therefore we believe that the direct coupling due to the gradient in the electron density in the ambient plasma may be the appropriate conversion mechanism for generation of electromagnetic waves from the Langmuir waves. By using the equation (16) for the parameters adopted in the present paper for 100 MHz and 13 kHz, we obtain 1.72×10^8 K and $7.\times10^3 K$ through Rayleigh scattering and 3.06×10^7 K and 7.66×10^8 K through direct coupling respectively at 100 MHz and 13 kHz for the effective temperatures of the Langmuir critical fluctuations.

As far as the electromagnetic emission at $2\omega_{pe}$ is concerned, if the generation mechanism is assumed to be the merging of beam excited Langmuir waves with back-scattered secondary Langmuir spectrum i.e., the modified idea of [7], the absorption due to decay of electromagnetic wave into two plasma waves is the most dominant absorption process. The optical depth due to such a decay is [33]:

$$\mu L = \frac{2e^2\omega_{pe}^2\kappa T_{eff}}{15\sqrt{3}m_e^2c^3v_{Te}^2v_{ph}}L. \tag{17}$$

For the parameters assumed for 100 MHz and 13 kHz $\mu L \ll 1$ and the brightness temperature T_B is given by:

$$T_B \simeq \alpha_1 L, \tag{18}$$

where the spontaneous scattering coefficient in this case is given by [33]:

$$\alpha_1 \simeq \frac{2}{15\sqrt{3}}\frac{e^2\omega_{pe}^2\kappa T_{eff}^2}{m^2c^3v_{Te}^2v_{ph}}L. \tag{19}$$

Therefore for $T_{eff} \simeq 10^{12} K$ we obtain $T_B \simeq 3.\times10^{10}$ K and 3.1×10^5 K at 100 MHz and 13 kHz respectively.

4. Discussion and Conclusions

Since the velocity of the electron beams responsible for type III bursts is known directly by measuring the drift rate of type III bursts in the dynamic spectrum, the ratio of beam to ambient electron density is an unknown quantity in type III phenomena. The critical beam density derived in the present paper where the phenomenon of critical fluctuations starts playing the dominant role in generation of Langmuir waves may give the required beam densities. Higher densities where the instability is playing the role in excitation of Langmuir fluctuations may be necessary to explain the brightest type III bursts. In the case of the interplanetary medium, the exact knowledge of electron density fluctuations is necessary to estimate the effective damping due to scattering of Langmuir waves on fluctuations. The problem of beam stabilization is not important in the case of critical fluctuations since the effective growth is almost negligible.

As far as conversion mechanism for the fundamental emission is concerned, the direct coupling between Langmuir and electromagnetic waves due density gradient in the ambient electron distribution appears to be the most favorable mechanism both in the corona as well as in interplanetary medium. The efficiency of conversion due to Rayleigh scattering is comparable to that due to direct coupling in the corona whereas it is much smaller at lower frequencies. But the efficiency of conversion at 100 MHz due to Rayleigh scattering is comparable to direct coupling. Therefore we believe that direct coupling may be the dominant process in converting the Langmuir waves into electromagnetic waves both in the corona as well as in the interplanetary medium.

In the case of second harmonic emission, the combination scattering may account for the emission at higher frequencies whereas it is too inefficient at lower frequencies thus requiring to invoke other mechanisms. Therefore we conclude that: (1) the phenomenon of critical fluctuations in the beam-plasma system may be very important for type III bursts, (2) the ratio N_b/N_e in weak type III bursts can be determined by the collisional damping in the corona, and by damping due to scattering on density fluctuations in the interplanetary medium, (3) since the instability does not develop in the case of critical fluctuations, the question of beam stabilization does not arise in the present model, (4) the direct coupling between Langmuir and electromagnetic waves appears to play a dominant role in converting the langmuir energy into electromagnetic energy at fundamental plasma frequency and (5) even though the combination scattering is capable of explaining the emission at twice the plasma frequency, it is too inefficient to explain the type III bursts at lower frequencies.

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5. References

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